AD-A212 497 TIC
SEP 20 1989
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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for Public Release; Distribution Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): GL-TR-89-0252	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Geophysics Laboratory (AFSC)	6b. OFFICE SYMBOL (If applicable): PHS
6c. ADDRESS (City, State, and ZIP Code): Hanscom AFB, Massachusetts 01731-5000	7a. NAME OF MONITORING ORGANIZATION
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)
8c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.
62201F	2311	G3	12

11. TITLE (Include Security Classification)
The Relation Between Convection Flows and Magnetic Structure at the Solar Surface

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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Reprint	FROM ____ TO ____	1989 September 12	7

16. SUPPLEMENTARY NOTATION * See Reverse for Author Affiliation
Reprinted from Adv. Space Res. Vol. 8, No. 11. pp(11)133-(11)139, 1988

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Solar Granulation, Solar Convection, Solar Magnetism

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
We describe recent results from the comparison of data from the Solar Optical Universal Polarimeter instrument on Spacelab 2 and magnetograms from Big Bear Solar Observatory. We show that the Sun's surface velocity field governs the structure of the observed magnetic field over the entire solar surface outside sunspots and pores. We attempt to describe the observed flows by a simple axisymmetric plume model. Finally, we suggest that these observations may have important implications for the prediction of solar flares, mass ejections, and coronal heating.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Claire Caulfield	(617) 377-4555	SULLP

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE: Unclassified

89 9 19 086

Cont of Block 16:

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Adv. Space Res. Vol. 8, No. 11, pp. (11)133–(11)139, 1988
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THE RELATION BETWEEN CONVECTION FLOWS AND MAGNETIC STRUCTURE AT THE SOLAR SURFACE

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ABSTRACT

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INTRODUCTION

In an earlier report /1/ we discussed the first results from observations made by the Solar Optical Universal Polarimeter (SOUP) during the Spacelab 2 (STS–19) mission of the Space Shuttle. At that time we pointed out that it is possible to measure large–scale [mesogranular (4"–12") and supergranular (20"–40")] cellular outflows by using granules as test particles of the velocity pattern. (Note: 1" = 1 arcsec = 720 km). Detailed analyses of many of the phenomena mentioned in /1/ have recently been published /2,3,4/. Another paper /5/ at this meeting discusses in detail the characteristics of these velocity patterns determined by the technique of local correlation tracking /6,7/.

In this report we will show the relationship between the mesogranular flows and the magnetic field distribution at the solar surface. Since many of these results have been published in /2/, we will only summarize that paper, and then discuss some additional analysis of these data.

OBSERVATIONS

We describe data obtained during orbit 110 of the Spacelab 2 mission, from 19:10:35 to 19:38:05 on 5 Aug 1985. Exposures were made each 2 s on 35 mm film of a solar area 166" by 250". In this study we have digitized a 119" by 131" area of the frame, using exposures at 10 s intervals. In addition, we analyze a 9 h series of magnetograms of the same solar area obtained at a roughly 10 min rate before, during, and after the SOUP data at the Big Bear Solar Observatory (BBSO) between 15:25:43 on 5 Aug 1985 and 00:50:54 on 6 Aug 1985. The magnetograms have been rectified, rotated, and scaled to fit the corresponding area of the SOUP image. Thus it becomes easy to compare, in detail, motions of the granulation field and the magnetic elements. Figure 1 (left) is a photograph of the SOUP white–light field, and Figure 1 (right) shows the magnetic field from BBSO.

ANALYSIS

By correlating /6,7/ successive white–light images of the solar granulation, one finds /5/ that granules are excellent tracers for large–scale motions at the solar surface. From the horizontal velocity vectors, one can compute the divergence of the flow [cf. equation (1) of /5/]. The flow vectors and the divergence for the area of Figure 1 are superposed in Figure 2. Bright regions are centers of outflow (sources) and dark areas are the locations of converging material (sinks).

If we place a uniformly–spaced grid of test particles ("corks") in the flow field, we observe /5/ that the corks are quickly expelled (within an hour or two) from the regions of positive divergence, then congregate into a network pattern in 4 to 8 h, after which they slowly (about one day) concentrate into sinks of negative divergence. An example of such cork motions is shown in Figure 5 of /5/.

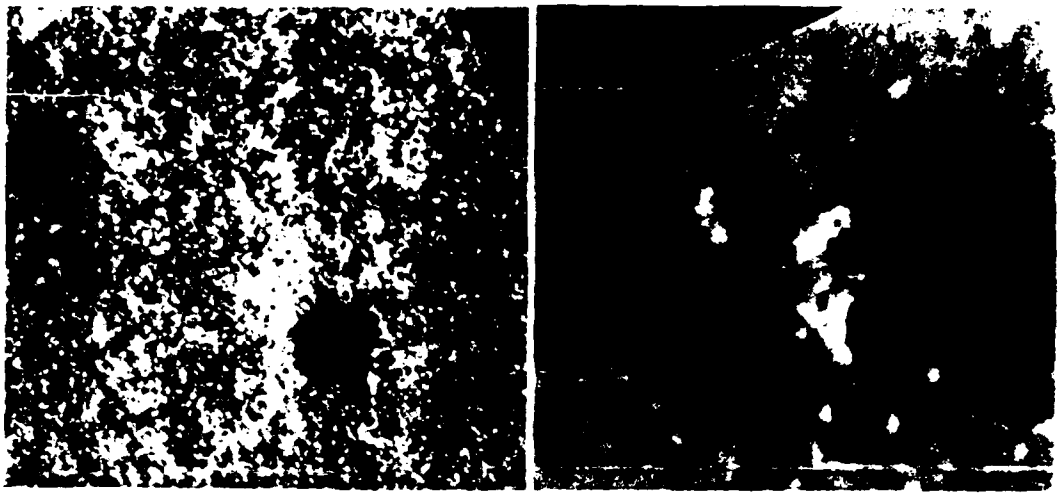

Fig. 1. Solar region analyzed in this study. (Left) SOUP white–light photo showing granulation, sunspot, and pores. (Right) Corresponding magnetogram from BBSO in which dark and light regions indicate opposite magnetic field polarity.

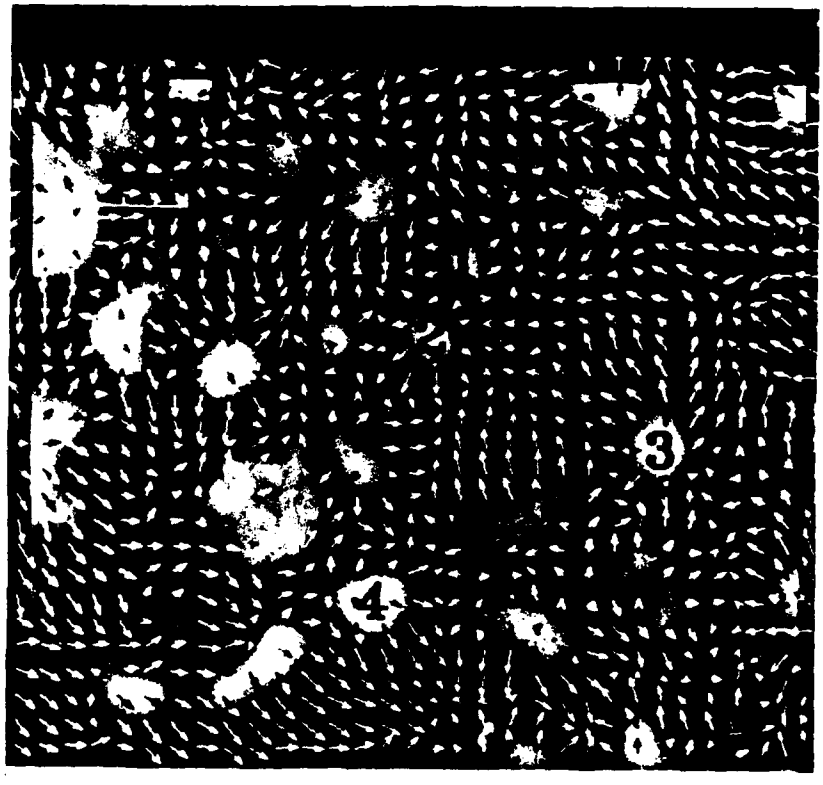

Fig. 2. Superposition of observed horizontal flow vectors and the divergence calculated from this velocity field. Bright regions are sources (four such features have beendark. The area shown is the same as in Fig. 1.

The major significance of this result becomes apparent if one considers the relation between these flows and the Sun's surface magnetic field. We find /2/ that magnetic features follow the same paths as the velocity corks. The well–known magnetic network which outlines the boundaries of supergranules is co–spatial with the cork distribution 8 to 16 h after the corks start from a uniform distribution. Some magnetic features converge to the same sink points as the corks, but much of the magnetic structure apparently prefers to remain as a network pattern.

The phenomena we have just described can best be seen by high speed cinematography. However, we summarize these results in Figures 3 and 4. In Figure 3 (left) we show the flow field of Figure 2 superposed on the magnetic field of Figure 1 (right). Figure 3 (right) is the superposition of the

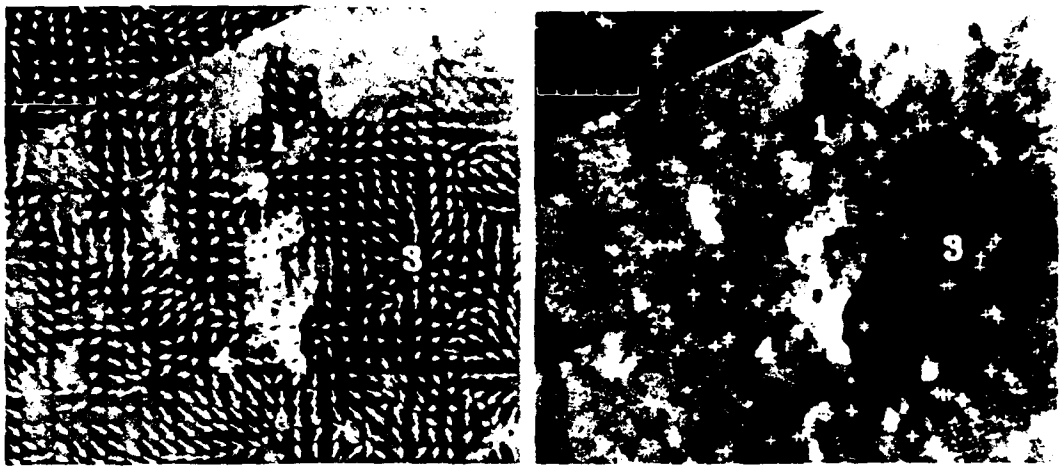

Fig. 3 Comparison among magnetic field structure, flow vectors, and velocity corks, for the area shown in Fig. 1 and Fig. 2. Superposition of magnetic field and (left) velocity vectors, (right) corks after 12 h.

magnetic field and the corks after 12 h. If one compares these two photographs, one can see easily that both the corks and the magnetic features concentrate wherever arrows indicate converging flow. To demonstrate this phenomenon more clearly, we have enlarged five small sections of Figure 3 and display them in Figure 4. Each of these examples illustrates the same point: Wherever there is an opposing flow field, the magnetic field becomes concentrated. Except in the regions of strongest field (sunspots and pores), the observations indicate that the field apparently does what the velocity field "dictates". That is, the data suggest the following relation between the magnetic and kinetic energy densities at that level in the solar atmosphere where gas motions determine the magnetic structure we see at the surface:

$$\tfrac{1}{2}\rho v^2 > \frac{B^2}{8\pi} \qquad (1)$$

in which v = gas velocity, B = magnetic density, and ρ = gas density. This relevant level is probably below the visible surface, since the observed concentrations of B (1000–1500 gauss), measured 100–200 km above the surface, are far stronger than the left–hand term of equation (1) can provide at this level, according to the limit placed by equipartition of energy (equation (1) with an = sign). Note, however, that numerous theoretical studies /8,9,10,11/ have shown that it should be possible to amplify the magnetic field to values much larger than the equipartition value, so it is by no means certain that the surface motions are unable to create the observed flux concentrations.

There may be important implications of these observations. By measuring the velocity fields, we hope to understand where magnetic fields will concentrate and be subjected to stresses. The SOUP velocities also show /5/ vortical (twisting) motions strong enough that the gas makes a full 360° turn in 2 to 3 h. If the footpoint of a magnetic flux tube embedded in such a flow pattern "obeys" this spiraling motion as it seems to follow the diverging and converging flows discussed above, it could become twisted into an unstable magnetic configuration. These observations indicate that it may become possible to predict those places on the Sun's surface most likely to produce solar flares, mass ejections, and coronal heating.

MODELING

Attempts are now underway /12/ to model these flows by simple potential functions which satisfy the continuity equation

$$\nabla \cdot (\rho\, \mathbf{v}) = 0 \qquad (2)$$

A function which satisfies equation (2) and represents radial horizontal outflow from an isolated source is:

$$v(r) = V\left[\frac{r}{R}\right] e^{-\left[\frac{r}{R}\right]^n} \qquad (3)$$

in which case the flow divergence (proportional to the vertical velocity) is

$$\Delta = \frac{V}{R}\left[2 - n\left[\frac{r}{R}\right]^n\right] e^{-\left[\frac{r}{R}\right]^n} \tag{4}$$

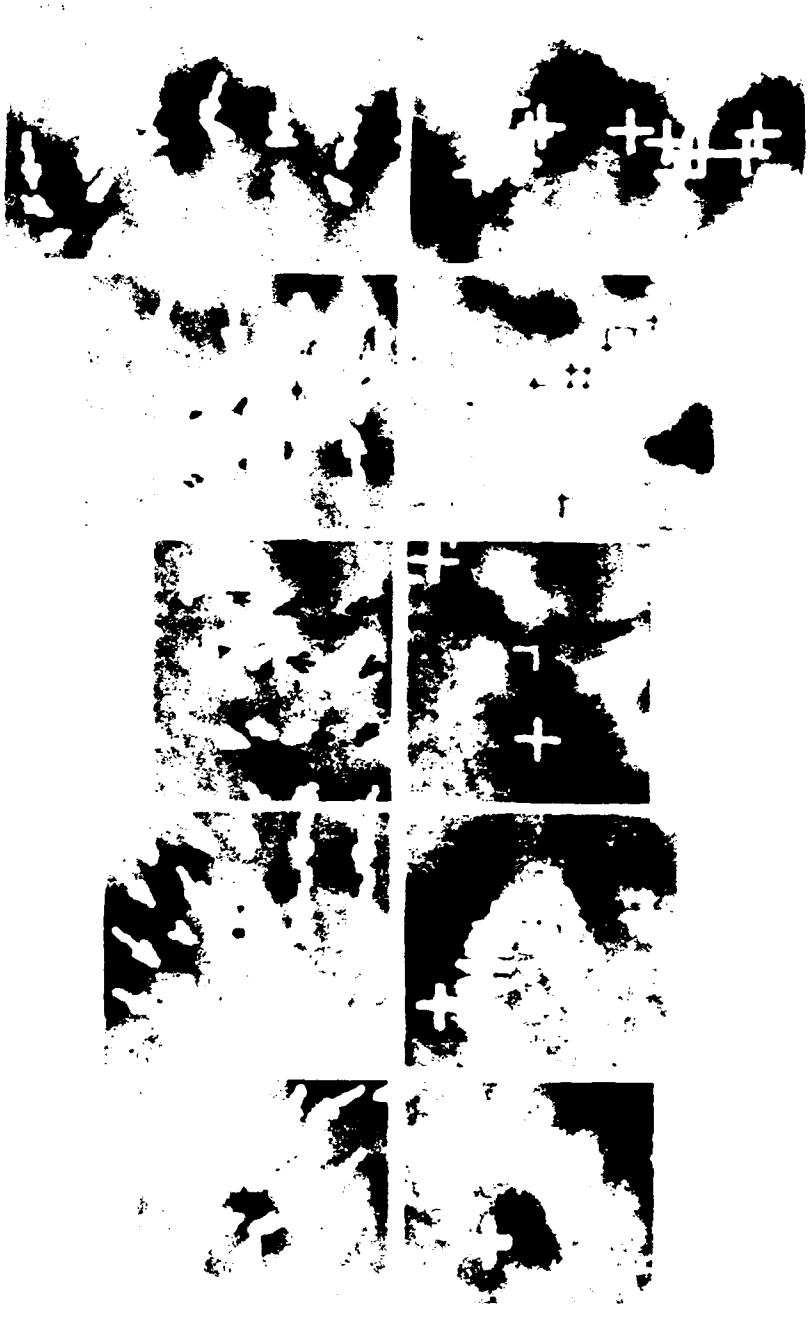

Fig. 4. Enlargements of five small sections of Fig. 3. In each case, the velocity vectors point toward a concentration of magnetic field and corks. The five areas shown run from top to bottom in Fig. 3. Particularly interesting are (second from top) a collision between outflow from the mesogranule labeled 2 and the sunspot, (third from top) a collision between outflow from the supergranule labeled 4 and the sunspot, and (bottom) convergence to a sink point. In this last example, the single cork visible is actually a superposition of five corks which have already converged at this site.

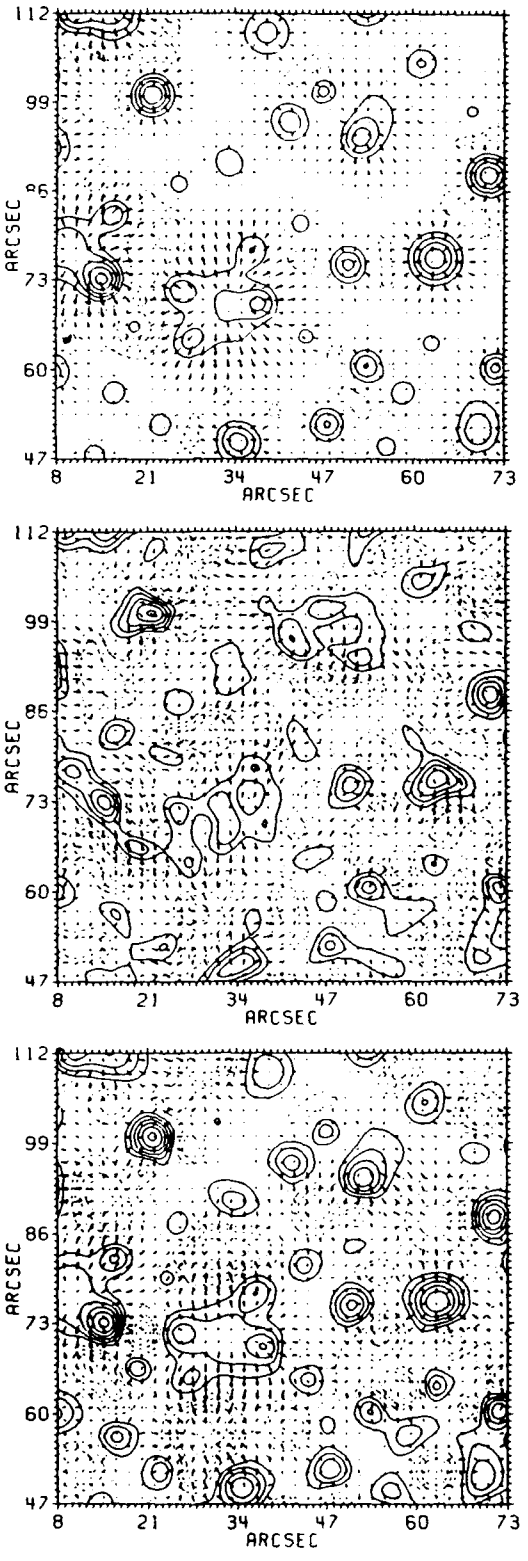

Fig. 5. Comparison of SOUP velocity vectors and divergence contours with those of axisymmetric plume model. (Center) SOUP data. (Top) Model containing only axisymmetric sources. (Bottom) Model having both sources and sinks. Solid lines are positive contours, dashed lines are negative contours, and short dashes (dots) are zero contours.

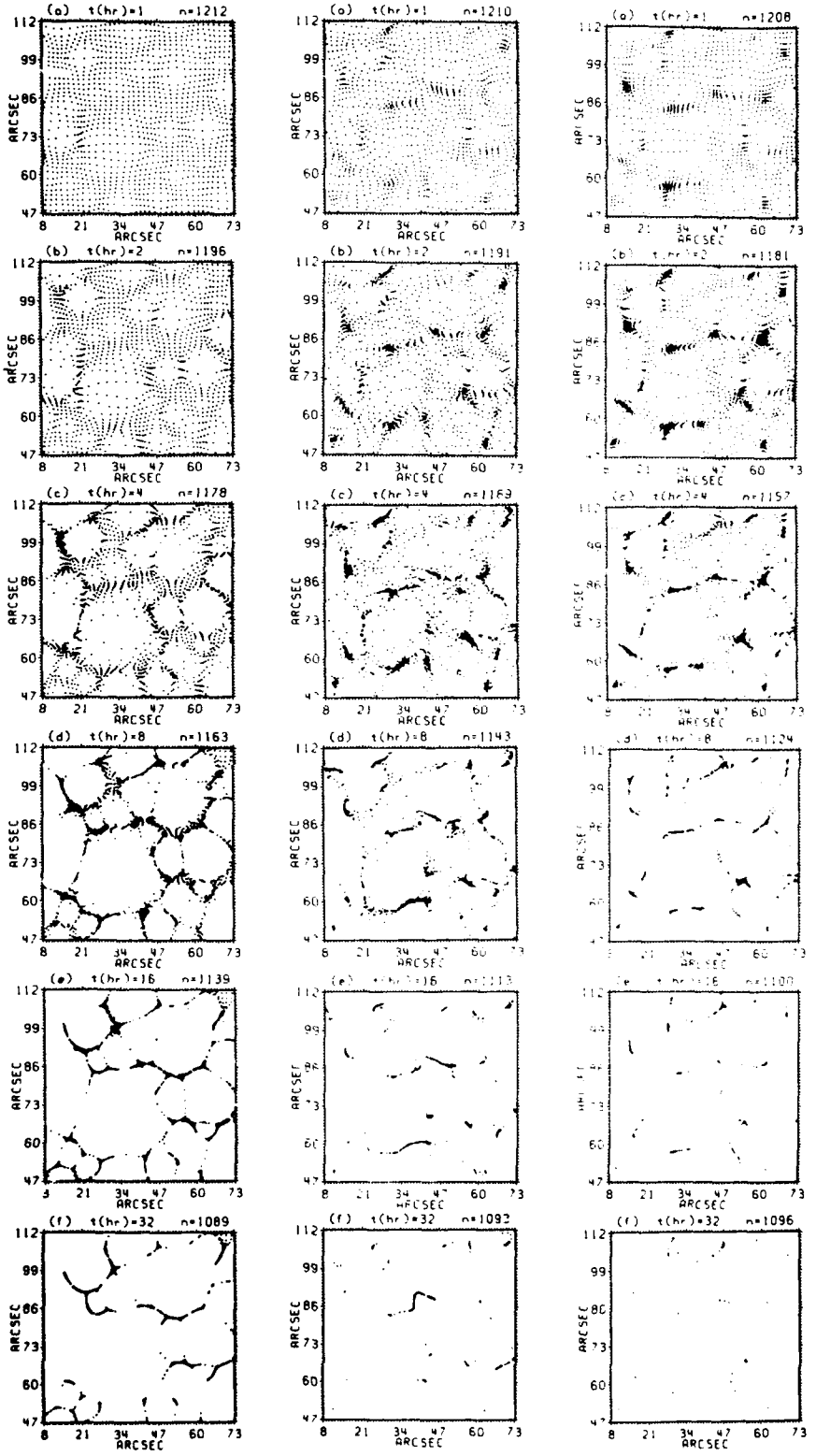

Fig. 6. Cork positions 1, 4, 8, 16, and 32 h after starting from a uniform distribution. Time increases downward in each column. (*Center*) SOUP data. (*Left*) Model with sources only. (*Right*) Model with both sources and sinks.

Each outflow in the observed data can be represented by such functions, where R is determined from the point where the observed Δ goes to zero and V is the central "strength" of the divergence maximum. We have found /12/ that n=2 works satisfactorily for most of the data analyzed. We then superpose all the observed maxima of Δ and compare the resulting model velocity field with the real data. Such a comparison is shown in Figure 5, with the modeled flow at the top, and the SOUP data in the center, for a 65" by 65" section of the SOUP image. Although the real data show distorted divergence contours, twisting and streaming motions, and convergence into sinks, none of which is included in the simple axisymmetric source model described by equations (3) and (4), nevertheless the two pictures agree in many details. A much closer comparison between SOUP and model data results if we include in the model the observed sinks. In this case we fit both sources and sinks with equation (4), but of course the strength V has a negative value for a sink. The resulting flow pattern is shown in Figure 5 (bottom).

A more severe test of the model is to compare the real and the model cork flows, which we do in Figure 6. The cork positions are shown 1, 2, 4, 8, 16, and 32 h after starting from a uniform distribution. The area is the same as in Figure 5. It is clear that the addition of sinks (right–hand column) makes the model cork behavior look more like the actual SOUP data (center column). However, the sources–only model (left–hand column) also agrees well with the real data for the first 4 to 8 h. After that, the corks (much like the actual magnetic field) remain in a network configuration for many hours, while the SOUP corks and the corks in the model with sinks quickly converge to the sink locations. Further model studies are in progress.

In the absence at the present time of low–noise solar data from space, ground–based observations similar to those from SOUP are being obtained at the Swedish Solar Observatory at La Palma (Canary Islands, Spain) and at the National Solar Observatory (Sunspot, NM, USA). Such studies, together with improved modeling of the flows, should prove most interesting in the prediction of solar flares and mass ejections during the 1989–1991 maximum of solar cycle 22.

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